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PENTAPURE IMPINGER EVALUATION

Douglas W. Cooper

GCA Corporation

Prepared for:

National Environmental Research Center

March 1975

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ABSTRACT

A novel spray scrubber, the Pentapure (Purity Corporation, Elk Grove Village, Illinois) was tested as part of a program to identify novel high efficiency fine particle control devices. The tests were made using the emissions from a gray iron foundry after they had exited from a spray cooling chamber. Their mass median aerodynamic diameter was 0.5 μm, as determined with cascade impactor samples. Inlet and outlet samples were taken with cascade impactors and with total mass measuring sampling trains. Total mass efficiency was found to be 10.0 ± 2.5 percent on this fine dust. The particle aerodynamic diameter for which the efficiency would be 50 percent was estimated to be between 2 and 4 μm, determined from cascade impactor analysis and from theoretical predictions of the performance. The pressure drop across the Pentapure scrubber was 1.5×10^3 N/m^2 (6" H_2O) and the measured efficiencies corresponded to those expected from venturi scrubbers having somewhat less pressure drop. The Pentapure is not an efficient fine particle collector.

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SECTION I

CONCLUSIONS

This evaluation was one of a series of such evaluations being conducted by the Environmental Protection Agency to identify novel devices which are capable of highly efficient collection of fine particulates. The Pentapure scrubber, made by Purity Corporation (Elk Grove Village, Illinois), had substantially less than 50 percent collection efficiency on fine particulates, those smaller than about 3 μm diameter, and thus did not satisfy this objective.

On a foundry dust having a mass median aerodynamic diameter of 0.5 μm after it exited a spray cooling system, the Pentapure scrubber gave 10.0 ± 2.5 percent overall mass efficiency. The aerodynamic diameter for which particle size the device would be 50 percent efficient was estimated to be between 2 and 4 μm from measurements with cascade impactors at the scrubber inlet and outlet; this confirmed mathematical estimates of the collection efficiency. The pressure drop across the Pentapure scrubber was 1.5×10^3 N/m^2 (6" H_2O) and the efficiencies achieved were equivalent to those for venturi scrubbers using pressures from 3.3×10^2 N/m^2 to 1.25×10^3 N/m^2 (1.3" H_2O to 5" H_2O).

SECTION II

RECOMMENDATIONS

The Pentapure scrubber does not give high efficiency for collecting fine particles and should not be investigated further for that purpose.

In those situations in which a low-energy venturi scrubber would be suitable, the use of the Pentapure scrubber might be considered as well.

SECTION III

INTRODUCTION

This work was done to evaluate the Purity Corporation impingement scrubber, the "Pentapure" scrubber, with respect to its collection efficiency for fine particles (diameters smaller than about 3 μm) and its power consumption and associated costs.

A diagram of the scrubber is shown in Figure 1. Dust laden air mixes with water spray. The mixture accelerates in the converging section, causing particle-droplet collisions and perhaps particle-particle collisions as well. The mixture is directed in a jet at the impingement surface and undergoes rapid deceleration, causing more collisions and causing the droplets, along with particles they have caught, to strike the surface, from which they run off and form a slurry. The air exhaust contains any uncaptured particulate material and droplets.

The tests were conducted at a gray iron foundry, with the collection efficiency determined by measuring the particle mass concentrations at the scrubber inlet and outlet. These emissions were generally in the fine particle range, the larger particles having been removed by cooling sprays and a separation chamber. Power consumption was determined from measurements of both the pressure drop across the scrubber and the volume air flow through the scrubber. Cost estimates are given which allow cost comparisons with other forms of particulate control equipment.

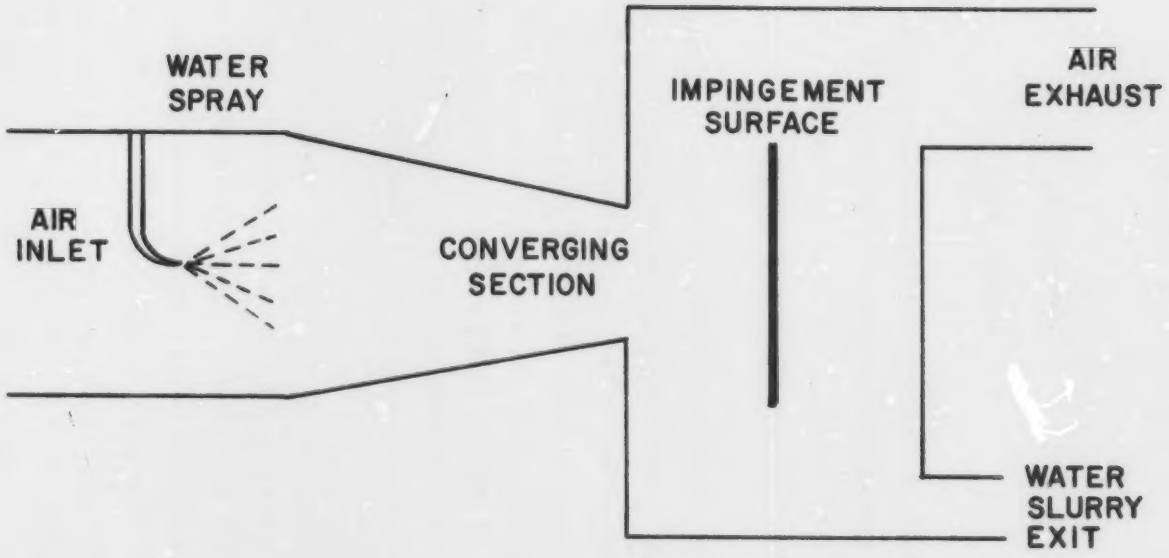

Figure 1. Schematic diagram of Purity Corp. impingement scrubber, the Pentapure scrubber

SECTION IV

COLLECTION EFFICIENCY TESTS

EQUIPMENT, PROCEDURE, AND RESULTS

Total Mass Efficiency

The tests were designed to give the fine particulate (< 3 μm diameter) collection efficiency of the scrubber section of the Purity Corp. installation, which will be referred to here as the scrubber. Figure 2 shows schematically the installation at the foundry and the location of the sampling equipment. Two kinds of efficiency determinations were made: total mass efficiency on the aerosol which entered the scrubber, and mass efficiency as a function of particle aerodynamic diameter on the same aerosols, using Andersen in-stack impactors.

The methods published in the Federal Register (December 23, 1971) were used as guidelines for the total mass efficiency determinations where feasible. If this were a test of conformance to "Standards of Performance for New Stationary Sources," there would be a legal requirement to adhere strictly to the test methods indicated in the Federal Register, but such is not the case. (Method 1, for example, says that "this method is not intended to apply to gas streams other than those emitted directly to the atmosphere without further processing." One is without a mandated test procedure in such cases and must proceed as good engineering judgment dictates.) What is required is a scientifically sound measurement of the inlet and outlet

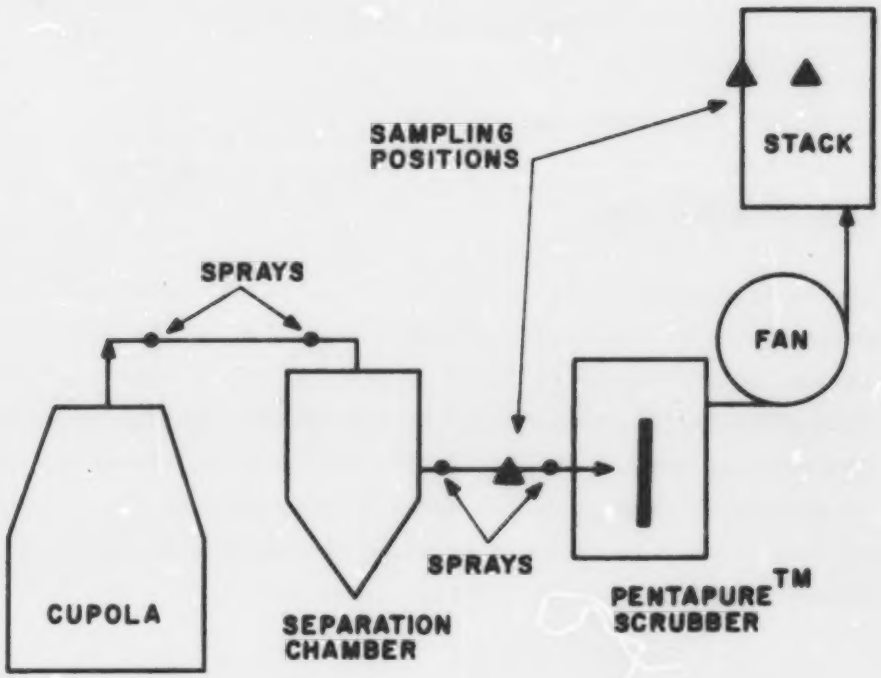

Figure 2. Schematic of sampling positions

mass throughputs, or, equivalently, inlet and outlet dry gas concentrations at standard conditions, as done here.

The positions of the sampling points on the traverse were as follows: At the inlet to the impinger scrubber, the samples were taken 3-1/2 diameters downstream from the separation chamber and about 1-1/2 diameters upstream from the converging section of the scrubber impinger. The duct diameter was 1.12 m (44 inches). We designed the tests for a forty-point traverse, twenty each on diameters vertical and horizontal in the horizontal ducting. Early tests indicated the presence of water for the first 10 cm or so at the bottom of the horizontal duct, so one of the tests (run 6) had 15 of 20 vertical traverse points; for the other two tests reported, the diameter was recalculated as 1.02 m (40 inches) and twenty-point traverses designed on the basis of this new diameter, 19 of 20 of these being taken in run 9 and 20 of 20 taken in run 10. As will be seen, the aerosol which reached the impinger scrubber after the separation chamber was one of fine particulates, precisely those for which spatial inhomogeneity is least. At the outlet, the ports were in a 0.92 m diameter (36 inches) stack, 6 diameters downstream from a flow obstruction and 2 diameters upstream from the outlet. Two perpendicular traverses of 12 points each were made here through ports labeled east and north. In both cases the points were chosen appropriate for equal-area sampling, following the guidelines in the Federal Register.

Determination of the stack gas velocity and flow rate followed Method 2 in the Federal Register cited above. The pitot tube was connected to the sampling probe. The gas velocity was calculated using Equation (2-2) of Method 2 and the dry gas volumetric flow rate calculated using Equation (2-3), based upon our measurements of water vapor and gas velocity.

Water vapor concentrations were obtained in two ways, following Method 4. The first was a determination of the amount of water caught by impingers and the second by assuming saturation at the stack temperature and

obtaining saturation water vapor concentrations from psychometric charts (Jorgenson, 1970). Both determinations are given in Table 1. To calculate the amount of dry gas sampled, the % H_2O obtained from the impinger samples was used.

The determination of the particulate emissions concentrations was done following, in general, Method 5 of the Federal Register cited. Figure 3 shows a schematic diagram of the Research Appliance Co. (RAC) sampling train used to do the sampling. Filters were pre-dried at least 24 hours with Drierite dessicant at about 70°F. After the tests, they were dried similarly. Table 2 gives the filter number, the initial weight, the weights after one day and after three days and the difference in the final weights of 13 filters, reweighed by a different operator. This tested for lack of adequate drying and for differences between operators. The mean weight change was 0.0024 g between weighings, which is to be compared with net loadings which averaged ~1 g, an insignificant weighing error of a few tenths of a percent of the net weights used to determine concentrations.

As a check on the flow determination, one can compare the inlet and outlet volume flow rates, dry air at STP. If there are no leaks in the control systems, these should be identical and their difference would be an estimate of flow determination error. Table 3 gives the inlet and outlet flows as measured for the runs indicated and gives the ratio of the two flows. The average absolute difference between these ratios and 1.00 is +0.041. The mean is 1.024. If there are no leaks, the flow determination error would be about 4 percent. The average absolute difference between the readings and the mean is 0.034.

Results for the determinations of mass concentrations and total mass efficiencies are summarized in Tables 4 and 5. Each diameter traverse is listed as a run. The inlet and the outlet each were traversed simultaneously. The process ran daily for about two hours. To achieve the

Table 1. STACK AND SAMPLE MOISTURE CONTENTS

Run	Location[a]	Stack temperature		Stack saturation % H_2O	Sample % H_2O by impingers
		^oF	^oC		
5	I	135	57	17.3	12.8
	O	79	26	3.3	10.5
6	I	123	51	12.5	7.8
	O	66	19	2.2	7.7
7	I	144	62	21.8	11.9
	O	81	27	3.6	11.1
8	I	120	49	11.5	13.1
1	O	104	40	7.3	9.4
9	I	126	52	13.6	11.1
	O	80	27	3.4	9.2
10	I	137	58	18.2	13.8
	O	85	29	4.1	10.7

[a] I = inlet, O = outlet.

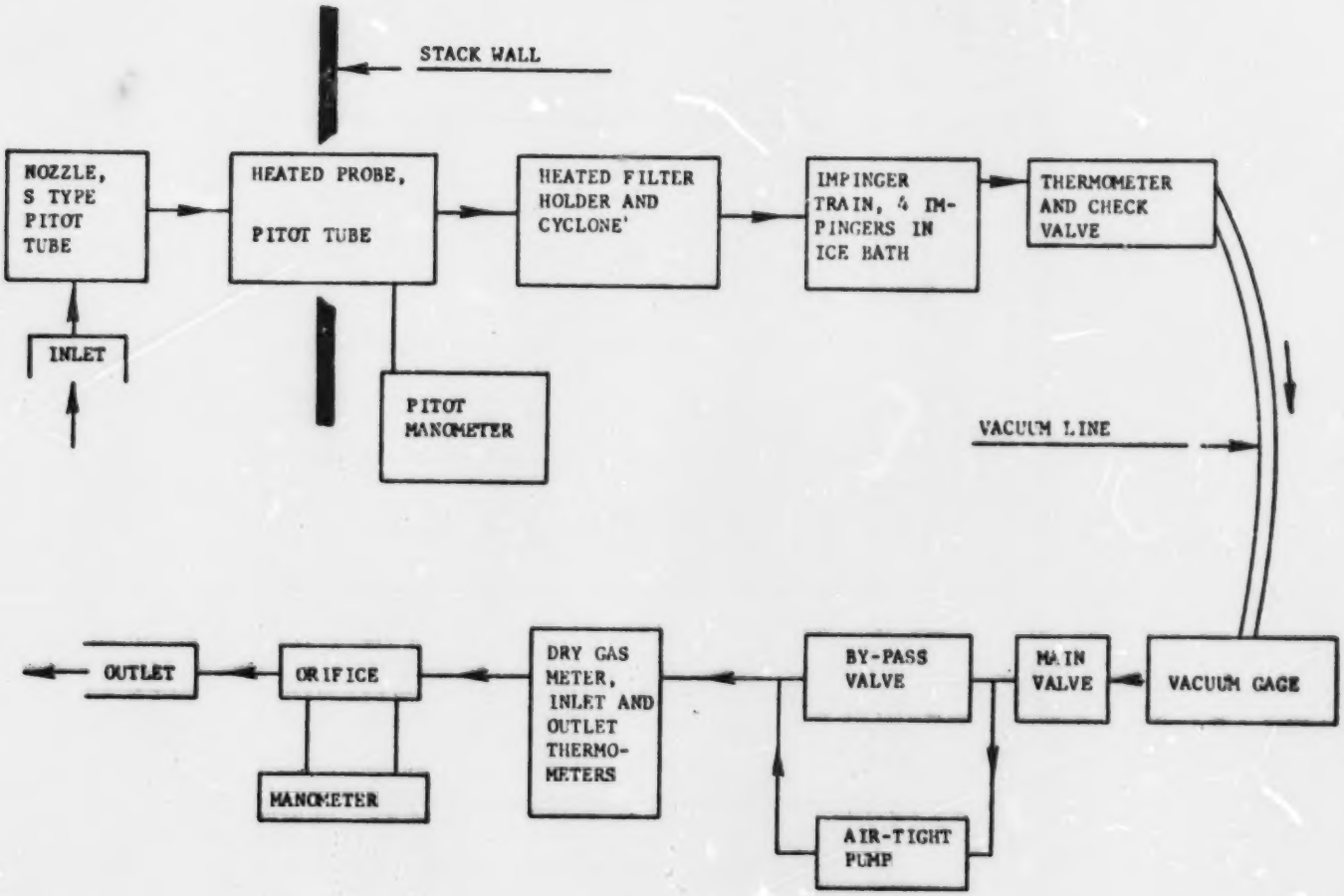

Figure 3. RAC train schematic for EPA - method 5 sampling

Table 2. RAC FILTER WEIGHINGS AND REWEIGHINGS

Filter no.	Run	Initial weights (g)	Final weights (g)		Final weight change (g)
			1-day drying	3-day drying	
277	1	0.6580	1.3016	1.3008	-0.0008
278	1	0.6938	1.8896	1.8975	+0.0079
279	2	0.6809	1.1395	1.1415	+0.0020
280	2	0.6592	1.6974	1.6976	+0.0002
251	3	0.6589	1.1140	1.1200	+0.0060
252	3	0.6693	2.0582	2.0644	+0.0062
276	4	0.6541	1.0000	0.9980	-0.0020
271	4	0.6814	1.8426	1.8411	-0.0015
238	5	0.6982	2.2653	2.2657	+0.0004
253	4	0.7047	1.2722	1.2585	-0.0137
202	5	0.7001	2.1610	2.1685	+0.0075
204	6	0.6827	2.2436	2.2530	+0.0094
205	6	0.7029	2.0283	2.0376	+0.0093

Table 3. COMPARISON OF INLET AND OUTLET FLOWS (DRY, STP)

Run	Flow (10^3 ft^3/min)		Outlet/inlet flow ratio
	Inlet	Outlet	
5 + 6	19.38	18.87	0.973
7 + 9	18.64	19.92	1.069
10 + 1	18.99	19.55	1.029

Table 4. RESULTS FOR TOTAL MASS EMISSIONS SAMPLING, INLET TO PURITY SCRUBBER

Run	Sample net weight (mg)	Stack concentrations		Dry STP stack flow (m^3/s)	$\left(10^3 \frac{ft^3}{min}\right)$	Percentage water content	Isokinetic percentage	Sample duration (min)	Traverse (horizontal/ vertical)
		(g/m^3)	(gr/ft^3)						
5	1661.3	0.871	0.3804	8.79	18.63	12.84	107.2	100.0	H
6	1679.4	0.990	0.4325	9.43	19.98	7.75	104.4	90.0	V
7	1505.5	0.903	0.3942	8.47	17.95	11.92	108.0	90.0	H
8	1265.9	0.793	0.3461	9.12	19.33	13.09	108.2	80.0	H
9	1348.0	0.740	0.3232	9.13	19.35	11.09	103.8	95.0	V
10	1285.0	0.824	0.3600	8.81	18.66	13.82	109.0	80.0	V
5 + 6	3340.7	0.902	0.3938	9.15	19.38	10.43	105.8	190.0	H-V
7 + 9	2853.5	0.818	0.3571	8.80	18.64	11.49	105.9	185.0	H-V
8 + 10	2550.9	0.808	0.3530	8.96	18.99	13.45	108.7	160.0	H-V

Comments

1. Probe not exactly 90^o to duct during vertical runs.
2. RUN 5 - 5 min. per pt., 20 pts.
   RUN 6 - 6 min. per pt., top 15 pts.
   RUN 7 - 5 min. per pt., first 18 pts.
   RUN 8 - 4 min. per pt., 20 pts.
   RUN 9 - 5 min. per pt., 19 pts.
   RUN 10 - 4 min. per pt., 20 pts.

Table 5. RESULTS FOR TOTAL MASS EMISSIONS SAMPLING, PURITY SCRUBBER, OUTLET CONCENTRATIONS, MASS EFFICIENCIES

Run	Sample net weight (mg)	Stack (g/m^3)	Concentration (gr/ft^3)	Dry, STP (m^3/S)	Stack flow (10^3 ft^3/min)	Water content	Isokinetic percentage	Traverse duration (min.)	Traverse perpendicular L = parallel	Efficiency (mass %)
5	1723.8	0.850	0.3711	8.48	17.97	10.50	85.4	96.0	L	2.44
6	1774.3	0.810	0.3539	9.35	19.80	7.71	83.6	96.0	P	18.17
7	1810.0	0.777	0.3395	9.19	19.47	11.13	90.4	96.0	L	13.88
1	1220.3	0.652	0.2849	8.84	18.72	9.44	90.7	80.0	P	17.68
9	1546.8	0.704	0.3076	9.63	20.40	9.17	94.1	83.0	P	5.03
10	1745.0	0.745	0.3252	9.63	20.41	10.74	90.0	93.0	L	9.67
5 + 6	3498.1	0.830	0.3624	8.91	18.87	9.07	84.5	192.0	L-P	7.97
7 + 9	3356.8	0.742	0.3239	9.40	19.92	10.19	92.3	179.0	L-P	9.30
10 + 1	2965.3	0.705	0.3080	9.23	19.55	10.19	90.4	173.0	L-P	12.75

Comments

1. RUNS 5, 6, 7 - 8 min per pt., 12 pts.
   RUN 1 - 8 min per pt., 9 & 11 skipped.
   RUN 9 - 8 min per pt., 10-1/2 pts.
   RUN 10 - 7 min per pt. for 10 pts.
   Keep: 12th Pt. sampled 8 min.

Method 5 minimum of 5 min per traverse point for the 40-point two-diameter traverse on the inlet required 200 min, so one diameter was done one day at the same time one diameter was being done at the outlet. The next day, the other pair of diameters were traversed. A complete cross-section is the sum of the two one-diameter traverses. Although there is a belief on the part of some that the Method 5 directions preclude taking the traverses on different days, this is not to be found in the specifications for Method 5. Normal operating procedure is to take one inlet-outlet pair of traverses followed by another pair of inlet-outlet traverses on the perpendicular diameters and to combine them, so that the only difference would be the degree to which day-to-day variations exceed hour-to-hour variations on processes which run for several hours. A measure of the variability is the standard deviation, and the inlet concentrations (Table 4) had a mean of 0.854 g/m^3 and a standard deviation of 0.088 g/m^3, which means about a 10 percent standard deviation due to differences between traverse positions and days. This indicates that neither the day-to-day variations nor the differences between sampling the inlet horizontally or vertically produced major variation in the data. Because the size distribution was primarily submicron, one would not expect major variations due to concentration gradients. Because the processes are very similar from day to day, one would not expect major variations in the mean concentrations. The data confirm these expectations (10 percent deviation in concentration).

The mean mass percentage efficiency was $(7.97 + 9.30 + 12.75)/3 = 10.01$ percent. The standard deviation of this number is $\left[\left((10.01 - 7.97)^2 + (10.01 - 9.30)^2 + (10.01 - 12.75)^2\right)/(3 - 1)\right]^{1/2}$ or 2.47 percent. Thus, the efficiency of the scrubber on the rather fine aerosol which reached it after traversing the sprays and the separation chamber was:

$$E_M = (10.01 \pm 2.47)\ \%$$

As will be shown, the particles were primarily submicron, on a mass basis, with a mass median aerodynamic diameter at the inlet of about 0.5 μm. Such fine particles are relatively easy to sample, but they are difficult for conventional scrubbers to collect.

The fineness of the aerosol was reflected in the relatively small amounts which deposited in the probe and cyclone portions of the total mass sampling train. Table 6 gives the average mass collected in these portions of the sampling train for six tests each at inlet and outlet of the scrubber.

Table 6. MEAN MASSES (SIX TESTS) CAPTURED BY FILTERS, PROBES, CYCLONES FOR INLET AND OUTLET TOTAL MASS SAMPLES

	Inlet		Outlet	
	mass (mg)	mass %	mass (mg)	mass %
Probe	50.4	3.46	93.5	5.70
Cyclone	48.8	3.35	53.4	3.26
Filter	1358.3	93.19	1489.8	91.02

Collection Efficiency Versus Aerodynamic Diameter

To measure the collection efficiency as a function of aerodynamic diameter, impactors (Andersen In-Stack Impactors) were used simultaneously upstream and downstream from the scrubber, as has been done elsewhere (for example by Horvath and Rossano, 1970, and Cooper and Anderson, 1974). Figure 4 gives a schematic of the sampling flow train used. An impactor was used to remove spray droplets larger than 15 μm aerodynamic diameter and heating tapes were used to dry those remaining. The impactors were operated at c.14 liter per min, 2.4×10^{-4} m^3/s (0.5 cfm). Dry air flow was measured with an orifice meter and the amount of moisture collected in the condenser noted.

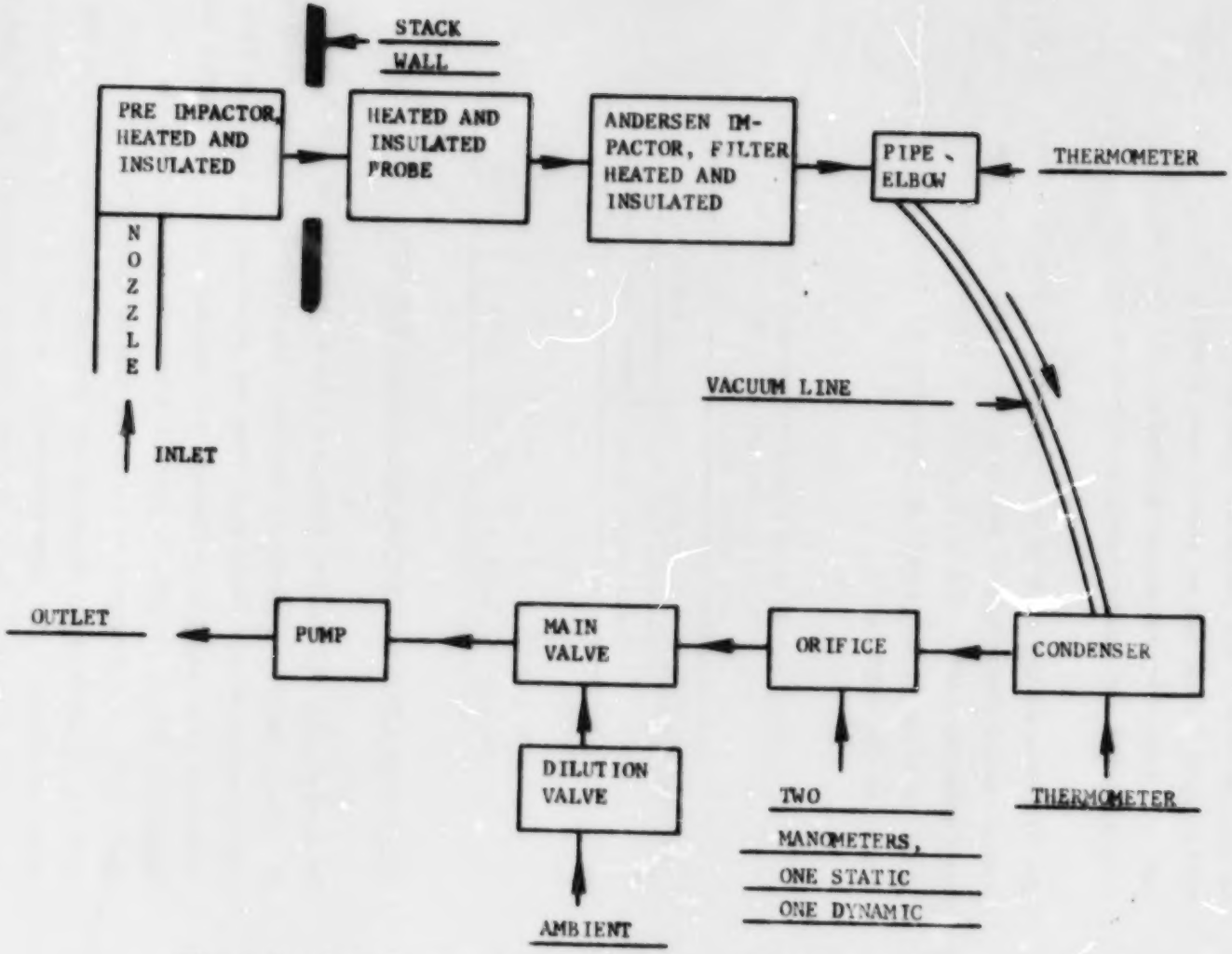

Figure 4. Andersen in-stack impactor sampling train schematic

The pre-impactor for removing spray droplets is shown in Figure 5. At 240 cm^3/s it has a calculated 50-percent efficiency for particles having an aerodynamic diameter of 15 μm, and about 10 percent at 10 μm, based upon equations for circular impactors having the same jet-to-wall and jet diameter dimensions (Fuchs, 1964).

The heater section is shown in Figure 6. At the 240 cm^3/s flow rate, particle losses due to gravity settling will be less than 5 percent for particles with aerodynamic diameters less than 10 μm, by calculation for turbulent flow (Fuchs, 1964). Using a heating tape of 3×10^2 W to wrap this heater and heat it, we measured an increase in gas temperature from ambient which corresponded to 1.8 w heat transfer. Initial use of this system for the scrubber evaluation revealed that this was not enough heat to evaporate all the droplets, so the heating capability was augmented by adding downstream from this heater 76 cm (30 in.) of 1.27 cm i.d. (1/2 in.) metal tubing wrapped with heating tape, which experiments indicated would add 1.2 w more heating power. This was sufficient heating; no longer were the symptoms of inadequate heating observed: excessively rapid increase in pressure drop across impactor filter, deterioration of the impactor collection substrates, presence of particles on the largest size classification stages.

Size Distributions and Collection Efficiencies

The impactor samples were taken approximately isokinetically. The problems with trying to take isokinetic samples is that there is a flow velocity profile, and one does not want to change the impactor flow to match the velocity because the flow rate determines the particle size classification intervals, which should not be changed during a run. Changing nozzle diameters at each sampling point is impractical. The samples were taken for 5 minutes or so, moved from one to another of about five traverse positions on each traverse diameter during the sampling. The more detailed data presentations are contained in Appendix A. The size classification intervals were calculated from

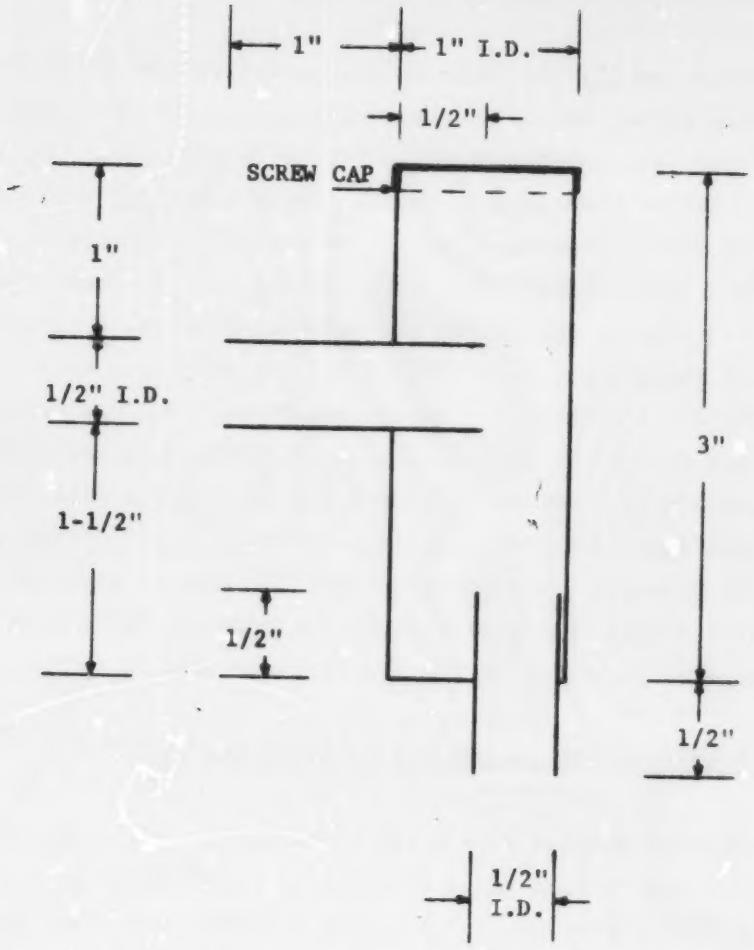

Figure 5. Pre-impactor for sampling in a spray

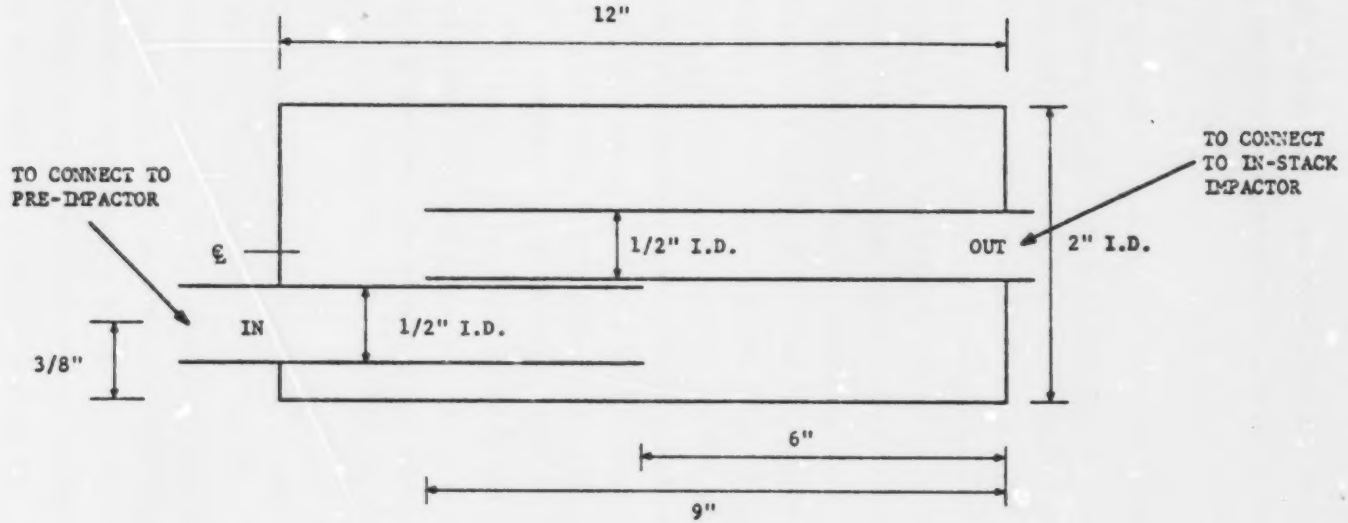

Figure 6. Heater/drier for sampling in a spray

formulas supplied by the manufacturer. The method for reducing the data from somewhat different flow rates to identical sizing intervals is given in Appendix B .

Figures 7 and 8 show the particle size distribution for the inlet and outlet aerosols as the cumulative mass percentage having aerodynamic diameters as large as or larger than the values on the abscissa. The mass median diameters were 0.5 μm at the inlet and 0.4 μm at the outlet, definitely a submicronic aerosol. The fineness of the aerosol made it difficult to evaluate collection efficiencies outside the fine particle range (0 to 3 μm) because the collection stages in the finest sizing intervals would approach the maximum recommended loadings (20 mg) before much material accumulated in the larger sizing intervals. As was done before (Cooper and Anderson, 1974), weight changes of 0.3 mg or less were treated as the inequality $\leq$0.3 mg in calculating efficiencies. Two traverses of mutually perpendicular diameters were combined to form one concentration value for each sizing interval by taking the total mass deposited and dividing by the total volume sampled. The numerical results of this analysis are presented in Tables 7 through 10. Graphically these results are depicted in Figure 9. The device was not an efficient collector of fine particulates, which is not an unexpected result considering the low pressure drop across the scrubbing section, an average of 6.06 in. H_2O = 1.51×10^3 N/m^2.

Possible explanations of the negative efficiencies (greater concentration of mass at the outlet in a size interval than at the inlet) include: agglomeration, deagglomeration, or other change in particle size distribution without increase or decrease in total mass; production of particles, such as by spray introduced between inlet and outlet; random data errors in the vicinity of zero efficiency; undetected systematic error. Particle production and random errors are discussed next.

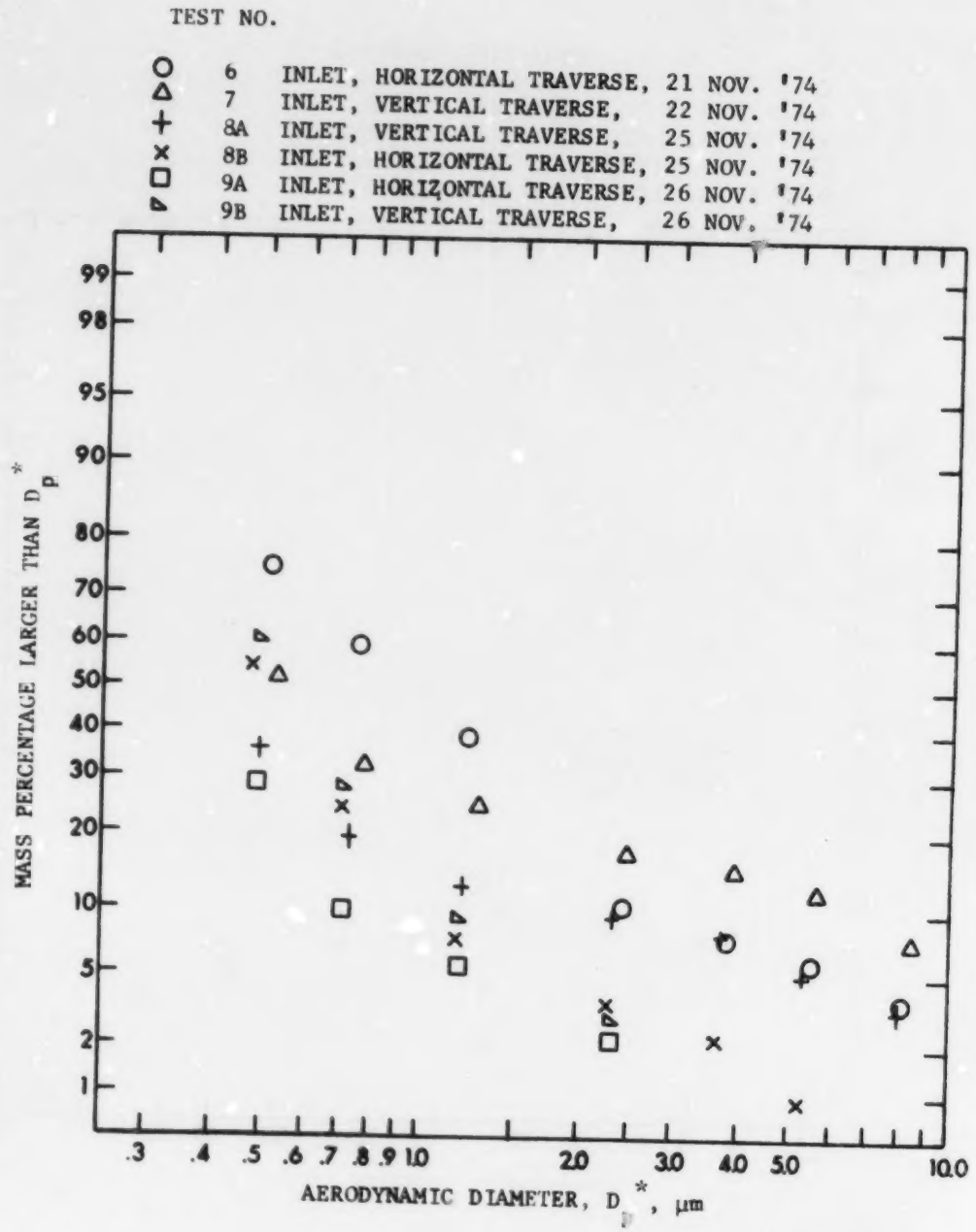

Figure 7. Inlet particle size distribution

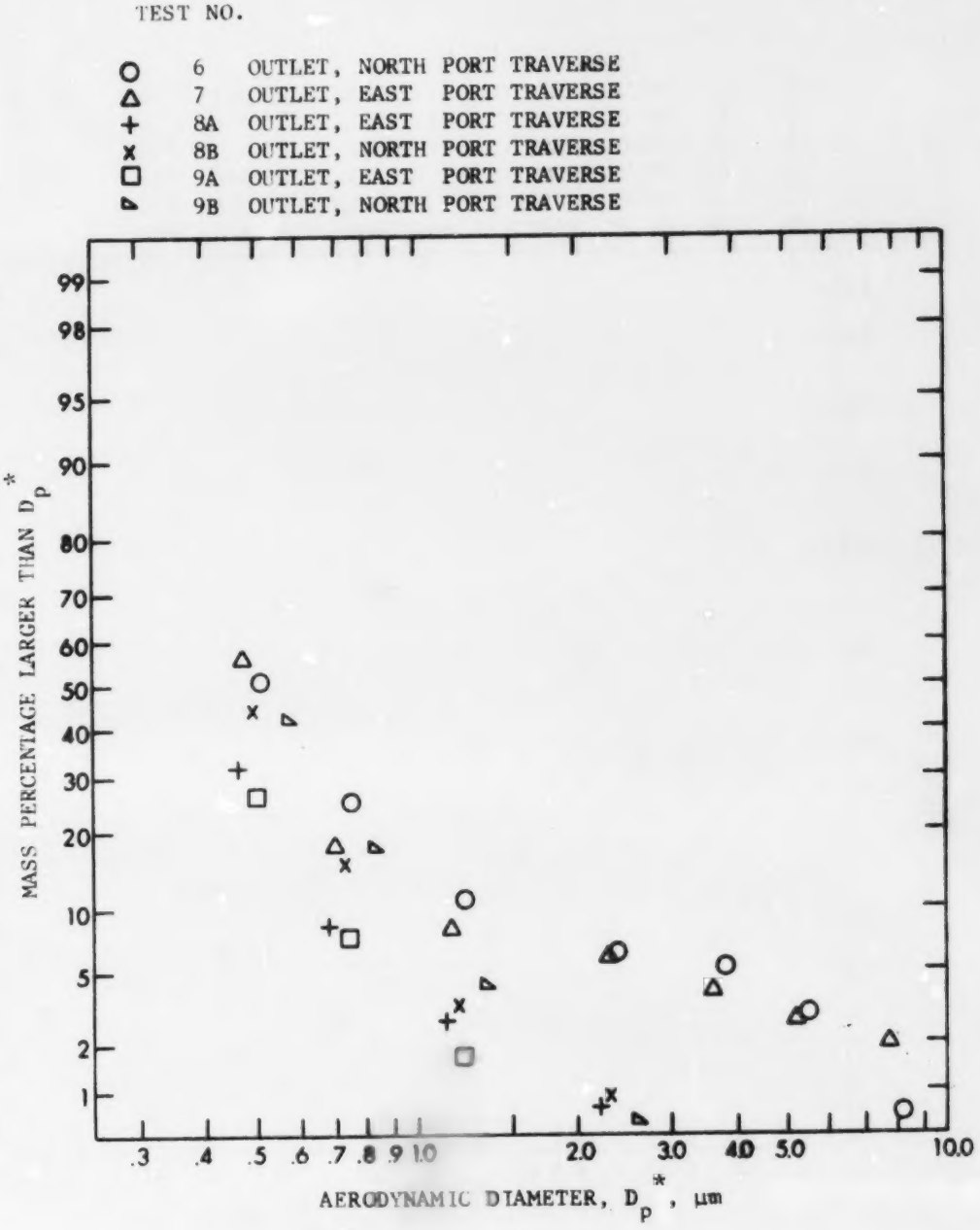

Figure 8. Outlet particle size distribution

Table 7. IMPINGEMENT SCRUBBER PARTICLE COLLECTION EFFICIENCIES FROM IMPACTOR DATA, TESTS 6 AND 7

Inlet		Outlet		Aerodynamic diameter (μm)	Collection efficiency (%)
Stage	Concentration (g/m^3)	Stage	Concentration (g/m^3)		
1	0.012	1	(≤) 0.004	12.8	≥58.3
2	0.013	2	(≤) 0.004	8.0	≥69.2
3	0.014	3	0.008	5.4	42.9
4	0.010	4	0.009	3.7	10.0
5	0.016	5	0.009	2.3	43.8
6	0.090	6	0.016	1.21	82.2
7	0.078	7	0.055	0.74	29.5
8	0.082	8	0.172	0.50	-109.8
Fines	0.149	Fines	0.252	<0.50	- 69.1

Table 8. IMPINGEMENT SCRUBBER PARTICLE COLLECTION EFFICIENCIES FROM IMPACTOR DATA, TESTS 8A AND 8B

Inlet		Outlet		Aerodynamic diameter (μm)	Collection efficiency (%)
Stage	Concentration (g/m^3)	Stage	Concentration (g/m^3)		
1	≤0.004	1	≤0.004	12.8	–
2	≤0.004	2	≤0.004	8.0	–
3	≤0.004	3	≤0.004	5.4	–
4	0.009	4	≤0.004	3.7	≥55.6
5	0.007	5	≤0.004	2.3	≥42.9
6	0.016	6	0.008	1.21	50.0
7	0.050	7	0.029	0.74	42.0
8	0.107	8	0.107	0.50	0.0
Fines	0.265	Fines	0.267	<0.50	- 0.7

Table 9. IMPINGEMENT SCRUBBER PARTICLE COLLECTION EFFICIENCIES FROM IMPACTOR DATA, TESTS 9A AND 9B

Inlet		Outlet		Aerodynamic diameter (μm)	Collection efficiency (%)
Stage	Concentration (g/m^3)	Stage	Concentration (g/m^3)		
1	≤0.004	1	≤0.004	12.8	
2	≤0.004	2	≤0.004	8.0	
3	≤0.004	3	≤0.004	5.4	
4	≤0.004	4	≤0.004	3.7	
5	≤0.004	5	≤0.004	2.3	
6	0.014	6	0.014	1.21	0.0
7	0.033	7	0.041	0.74	-24.2
8	0.085	8	0.081	0.50	4.7
Fines	0.203	Fines	0.244	<0.50	-20.2

Table 10. MEAN COLLECTION EFFICIENCY, IMPACTOR DATA

Mean aerodynamic diameter (μm)	Mean efficiency (%)
3.0	43.8
1.75	44.1
0.98	15.8
0.62	-38.5
0.25	-30.0

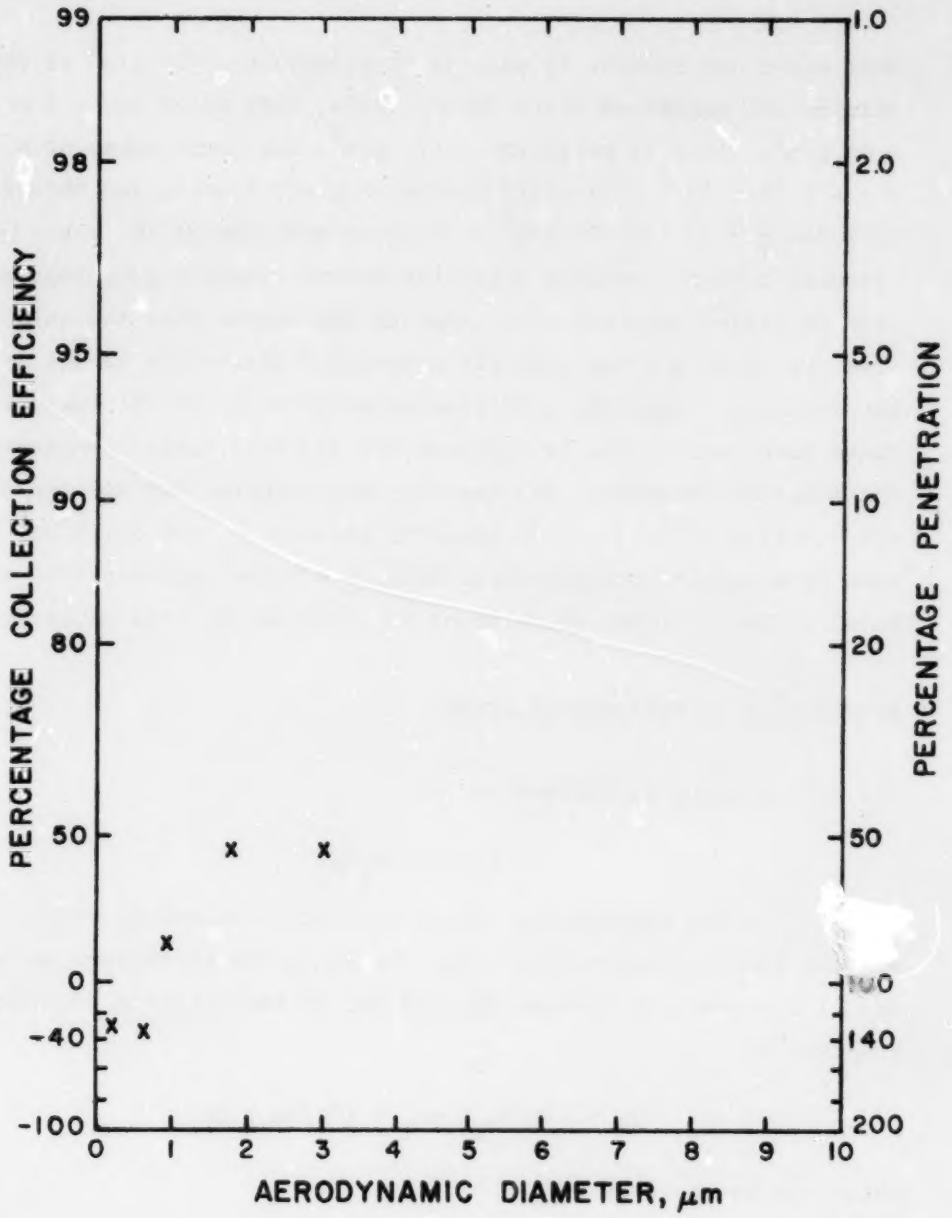

Figure 9. Collection efficiency versus aerodynamic diameter, data means for Pentapure scrubber

Particle Generation by Scrubber

Hard water may contain as much as 30 gr/gallon = 510 g/m^3 of dissolved calcium and magnesium salts (Rose, 1966), soft water has $\lesssim$ 5 gr/gallon = 86 g/m^3. At ~ 10 gr/gallon = 171 g/m^3, the total spray of 85 gallon/min = 0.46 x 10^{-3} m^3/s would produce a grain loading for this air flow of 0.044 gr/ft^3 = 0.101 g/m^3. Whatever fraction of the spray was introduced between scrubber inlet and outlet sampling positions would tend to lessen measured efficiency to the degree that the solids formed from the spray and not captured outweighed the solids caught by spray and scrubber. Negative efficiencies would occur if the spray introduced more solids than it captured for any size interval measured with the Andersen impactor. The negative efficiencies for the finest aerosol fraction ($\leq$ 0.50 μm) in impactor tests 6, 7, and 8A, B and 9A, B came from outlet concentrations being $\lesssim$ 0.1 g/m^3 greater than the inlet concentrations, which might be explained by this mechanism.

Sensitivity to Measurement Error

The efficiency E is defined as the

$$E = 1 - m_2/m_1$$

where m_2 is the appropriate outlet concentration and m_1 is the corresponding inlet concentration. The change in the efficiency measurement, dE, with respect to changes dm_1 and dm_2 in the measured concentrations is given by

$$dE = (\partial E/\partial m_1)\, dm_1 + (\partial E/\partial m_2)\, dm_2$$

which can be shown to be

$$dE = (m_2/m_1)\,(dm_1/m_1) - (dm_2/m_1)$$

which has an absolute magnitude

$$|dE| \leq |(1 - E)| \left(\left| \frac{dm_1}{m_1} \right| + \left| \frac{dm_2}{m_2} \right| \right)$$

As the efficiency tends to zero, the fractional errors are magnified as this equation indicates. If the concentrations have a 5-percent relative error (dm_1/m_1, dm_2/m_2 = 0.05), the error in the efficiency determination would be $dE \lesssim \pm$ 10 percent at E = 0.0 percent, $dE \lesssim \pm$ 5 percent at E = 50 percent and $dE \lesssim \pm$ 1 percent at E = 90 percent.

In our laboratory tests using these two impactors to sample simultaneously an iron oxide aerosol, we found a correlation coefficient averaging better than 0.998. One of these two tests is shown in Table 11. From the data from sizing intervals having 0.3 mg or greater, the average absolute percentage difference between the two impactor concentration determinations was 13 percent, which means the individual errors dm_1/m_1 and dm_2/m_2 were about one-half this; at zero efficiency, the average absolute difference from zero of the measurements would be about 13 percent, as many negative as positive. This would also partially explain some negative efficiency values.

In another set of tests, these made with the Andersen In-Stack Impactors side-by-side at the outlet of a power plant baghouse (Nucla, Colorado), the total mass concentrations determined by the two impactors were compared for 22 separate runs. The average absolute difference between the impactors was 74 percent of the geometric mean concentration and the average difference was 15 percent, indicating that most of the error was random rather than a consistent bias. These differences were substantially higher than those noted in the laboratory tests, one reason for which may be the unusually low concentration (0.0034 gr/scf = 0.0078 g/m^3) and long sampling time (6 hr). A more important reason was the difference in the size distributions,

Table 11. DATA FROM TWO ANDERSEN MARK III CASCADE IMPACTORS SAMPLING SAME IRON OXIDE AEROSOL (MAPICO BLACK) AT 470 cm^3/s

Impactor Stage	Mass collected		Percentage of total mass		Cumulative mass percentage		Effective Diameter (μm) D_{50}
	Impactor #4601	Impactor #4602	Impactor #4601	Impactor #4602	Impactor #4601	Impactor #4602	
1	0.4	0.2	2	1	2	1	9.6
2	0.3	0.2	2	1	4	2	6.0
3	0.6	0.4	3	2	7	4	4.0
4	0.8	0.7	5	4	12	8	2.75
5	2.0	1.9	11	11	23	19	1.75
6	9.6	9.7	54	55	77	74	0.9
7	3.3	3.8	19	22	96	96	0.54
8	0.1	0.2	1	1	97	97	0.36
Filter	0.6	0.5	3	3	100	100	
Total Mass	17.7	17.6	100	100			

Correlation coefficient: 0.998

the power plant aerosols having a mass median diameter of 8.7 μm, about four times larger than the laboratory aerosols and ten times larger than the foundry aerosol; the larger aerosols are more prone to unrepresentative sampling and to losses. The differences between impactors are believed to have been nearer those experienced in the laboratory tests than those experienced with the baghouse effluent tests.

THEORETICAL EFFICIENCY COMPARED WITH EXPERIMENTAL

The Scrubber Handbook gives the following formula for the penetration of a venturi scrubber:

$$Pn = \exp\left(2\, Q_L\, u_g\, \rho_L\, D_d\, F(K_p, f)/55\, Q_g\, \mu_g\right)$$

where Q_L = volume flow of scrubbing liquid, cm^3/s
u_g = gas velocity at scrubber throat, cm/s
ρ_L = scrubbing liquid density, g/cm^3
D_d = scrubbing droplet mean diameter, cm
$F(K_p, f)$ = inertial collision function
Q_g = gas volume flow, cm^3/s
μ_g = gas viscosity, poise

The function $F(K_p, f)$ depends upon a Stokes parameter, K_p, given by

$$K_p = u_g\, d_{pa}^2/9\, \mu_g\, D_d \quad ,$$

where d_{pa} is the particle aerodynamic diameter ($\sqrt{g/cm^3}$cm), and F depends upon the parameter f, which is determined empirically and includes effects of mean gas droplet relative velocity and droplet-particle wetting. In the range where collection is appreciable ($K_p > 1$), an approximate form given in the Scrubber Handbook for F is

$$F(K_p, f) = -\,0.156\, K_p\, f^2 \quad .$$

The resulting expression for the penetration becomes:

$$Pn = \exp\left(- (6.3 \times 10^{-4})\ f^2\ Q_L\ u_g^2\ \rho_L\ d_{pa}^2 / Q_g\ \mu_g^2\right)$$

The factor f is usually between 0.25 and 0.5. Here Q_L/Q_g was $\lesssim$ 85 gal/20,000 ft^3 = 0.57×10^{-3}. The gas flow at the throat was 20,000 ft^3/min through a 2-foot diameter opening or 6,366 ft/min, which is 32.4×10^2 cm/s = u_g. The scrubbing liquid density was 1 g/cm^3 and the air viscosity 2.1×10^{-4} poise. For f = 0.5 and $d_{pa} = 1 \times 10^{-4}$ cm $\sqrt{g/cm^3}$:

$$Pn = \exp\left(- \frac{(6.3 \times 10^{-4})(0.5)^2(0.57 \times 10^{-3})(10.5 \times 10^6)(1 \times 10^{-4})^2}{(4.41 \times 10^{-8})}\right)$$

$$Pn = 0.808.$$

Table 12 gives the calculated pentrations using this formula for both f = 0.25 and f = 0.50. These calculations are approximate, partly because the scrubber geometry is somewhat different from that of the usual venturi, though not so different that their major collection mechanism differs: the impaction of particulate material on droplets, followed by the capture of the droplets.

In the Scrubber Handbook, the following equation is derived to correlate fractional penetration, Pn, of particles having given aerodynamic diameter, d_{pa}, with pressure drop, ΔP:

$$Pn = \exp\left(- \frac{6.1 \times 10^{-9}\ (d_{pa})^2\ \Delta P\ f^2\ \rho_L}{\mu_g^2}\right)$$

Table 12. APPROXIMATE THEORETICAL EFFICIENCIES FOR PURITY CORP. IMPINGEMENT SCRUBBER

Particle aerodynamic diameter (μm)	Assuming f = 0.25		Assuming f = 0.50	
	Fractional penetration (Pn)	Percentage efficiency (%)	Fractional penetration (Pn)	Percentage efficiency (%)
0.5	0.987	1.3	0.948	5.2
1.0	0.948	5.2	0.808	19.2
2.0	0.808	19.2	0.425	57.5
3.0	0.618	38.2	0.146	85.4
4.0	0.425	57.5	0.0327	96.7
6.0	0.146	85.4	0.00046	99.95
8.0	0.0327	96.7	1×10^{-6}	100
10.0	0.0048	99.5	--	100

where μ_g = gas viscosity, poise

d_{pa} = particle aerodynamic diameter, $\mu m \sqrt{g/cm^3}$

ρ_L = scrubbing liquid density, g/cm^3

ΔP = pressure drop across scrubber, cm H_2O (980 dynes/cm^2, 98 N/m^2)

f = empirical constant, related to relative gas/liquid velocity and coverage

Figure 10 is a corrected version of one from the Scrubber Handbook, the aerodynamic diameters indicated for f = 0.25, which that reference indicated was best, and for f = 0.5, which Calvert (1974) indicated was the best fit for coal-fired power plant emissions (fly ash). The dependence on f is striking, being just as strong as the dependence upon particle size; doubling f halves the particle size caught with a given efficiency at a given pressure drop. For the same particle size, the factor of 2 in the different f values corresponds to a factor of 4 in the pressure drop required to achieve a particular penetration.

The scrubber is not identical to a venturi scrubber, but basically both types use the acceleration and deceleration of the air to produce relative velocity gradients between the airborne particulates and the collecting droplets. The Purity scrubber collection efficiency is expected to be related to the pressure drop across the scrubbing section in much the same way the venturi scrubber efficiency is. Figure 10 has the penetration versus pressure drop curves for typical venturi scrubber performance (from Scrubber Handbook, by Calvert, et al., 1972). The open circles and triangles on the figure are the measured efficiencies for the Purity scrubber at the aerodynamic diameters indicated.

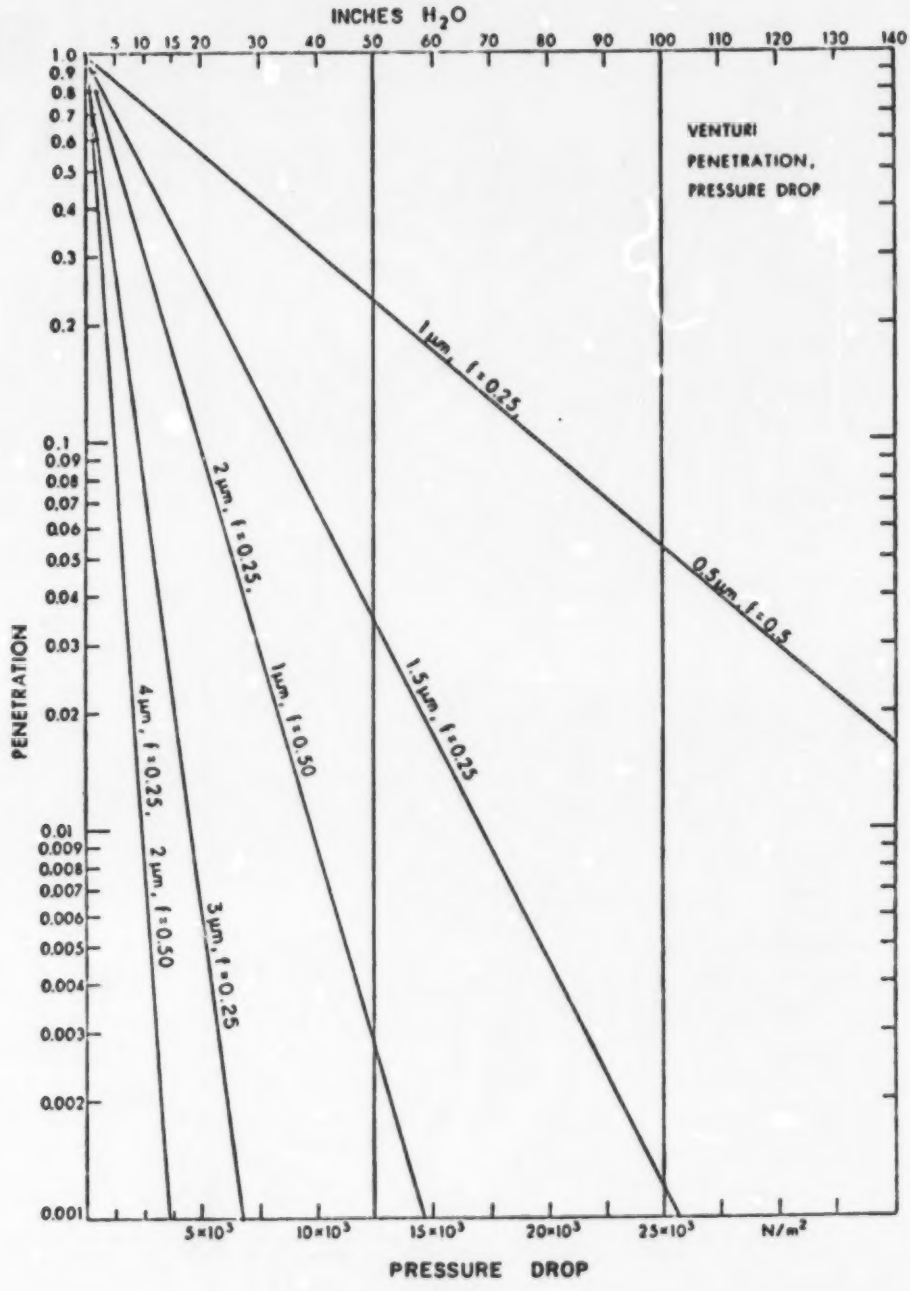

Figure 10. Venturi pressure drop and efficiency for different f factors and particle diameters (corrected version of Scrubber Handbook figure)

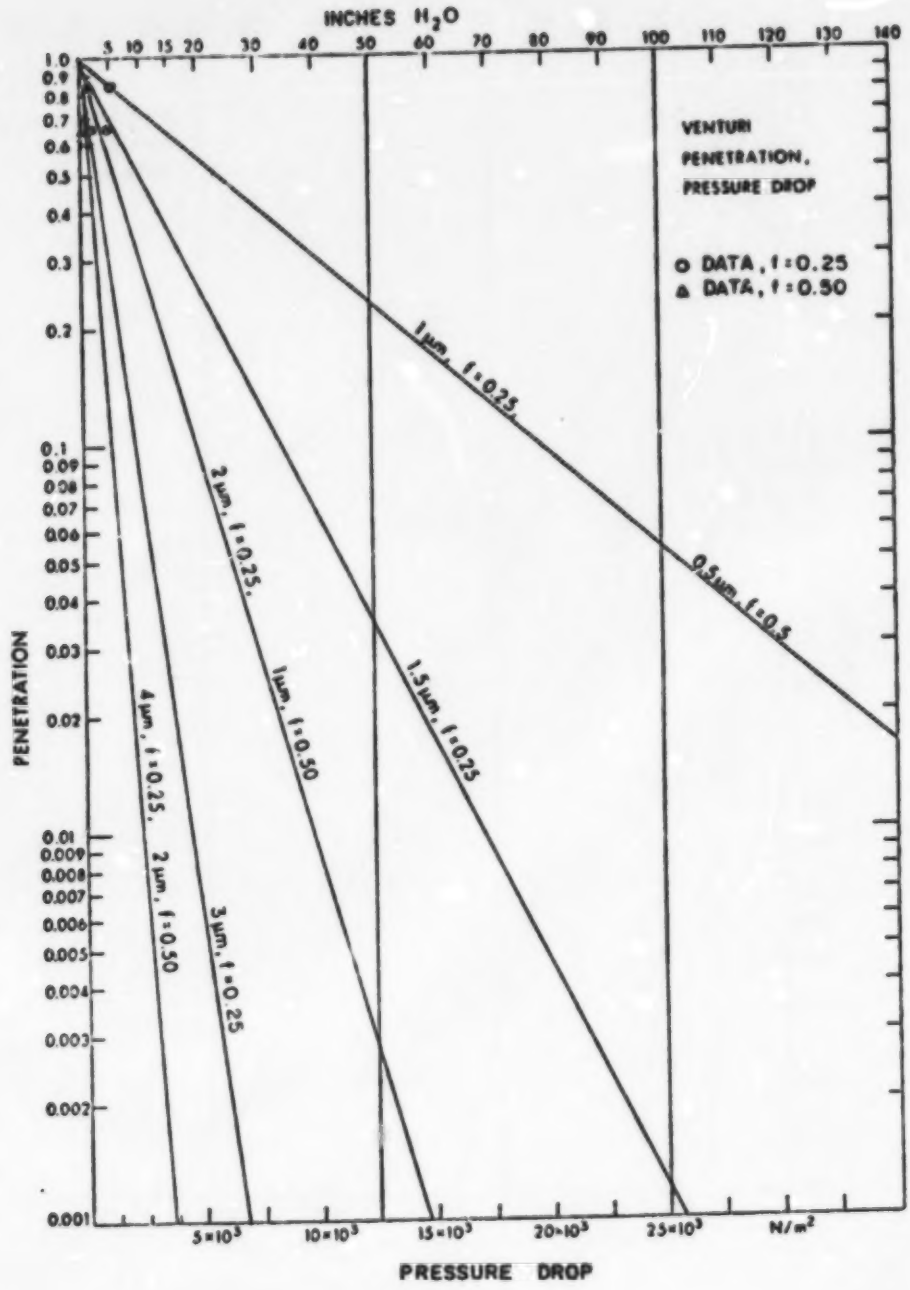

Figure 11. Corrected venturi performance curves with Pentapure scrubber data added

Depending upon which f factor value is more appropriate for this situation (0.25 or 0.5), the device was equivalent to a venturi with 0.75×10^3 to 1.8×10^3 N/m^2 (3 to 7 in. H_2O) pressure drop or 0.19 to 0.45×10^3 N/m^2 (0.75 to 1.8 in. H_2O). From the Scrubber Handbook equation 5.3.6-12, the following equation can be derived to give the pressure, Δp (N/m^2), required for a venturi scrubber to have 50 percent efficiency and particle aerodynamic diameter d_{pa}:

$$\Delta p = 1.114 \times 10^2 \, \mu_g^2 / \rho_L \, d_{pa}^2 \, f^2$$

Values derived from this equation are given in Table 13 and Figure 12.

Figure 12 is based upon the next to last table, Table 12, and has the non-negative impactor data points for the scrubber superimposed on a graph of the percentage efficiency versus particle aerodynamic diameter with two different f values, showing a 50 percent efficiency somewhere around 2 μm to 4 μm aerodynamic diameter.

The final result of a theoretical analysis performed on this type of scrubber by Midwest Research Institute was that the particle size for which the efficiency would be 50 percent was 3 μm for a 2.8 g/cm^3 density particle, which corresponds to a 5 μm aerodynamic diameter (K.P. Ananth, MRI, personal communication, December 1974).

In summary, the theoretical analysis and the experimental results indicate that the collection efficiency reaches 50 percent between 2 and 4 μm aerodynamic diameter and increases for the larger particle sizes, but decreases for the smaller sizes, at least down to a few tenths microns.

Table 13. THEORETICAL PRESSURE DROP NEEDED FOR 50 PERCENT COLLECTION EFFICIENCY AT THE LISTED PARTICLE SIZES FOR A VENTURI SCRUBBER

Particle aeroydnamic diameter (μm)	Pressure drop			
	f = 0.25		f = 0.50	
	N/m^2	$"H_2O$	N/m^2	$"H_2O$
1	5.8×10^3	24	1.44×10^3	5.8
2	1.44×10^3	6.0	0.36×10^3	1.5
3	0.64×10^4	2.6	0.16×10^3	0.64
4	0.36×10^3	1.5	90	0.36
5	0.23×10^3	0.93	57	0.23

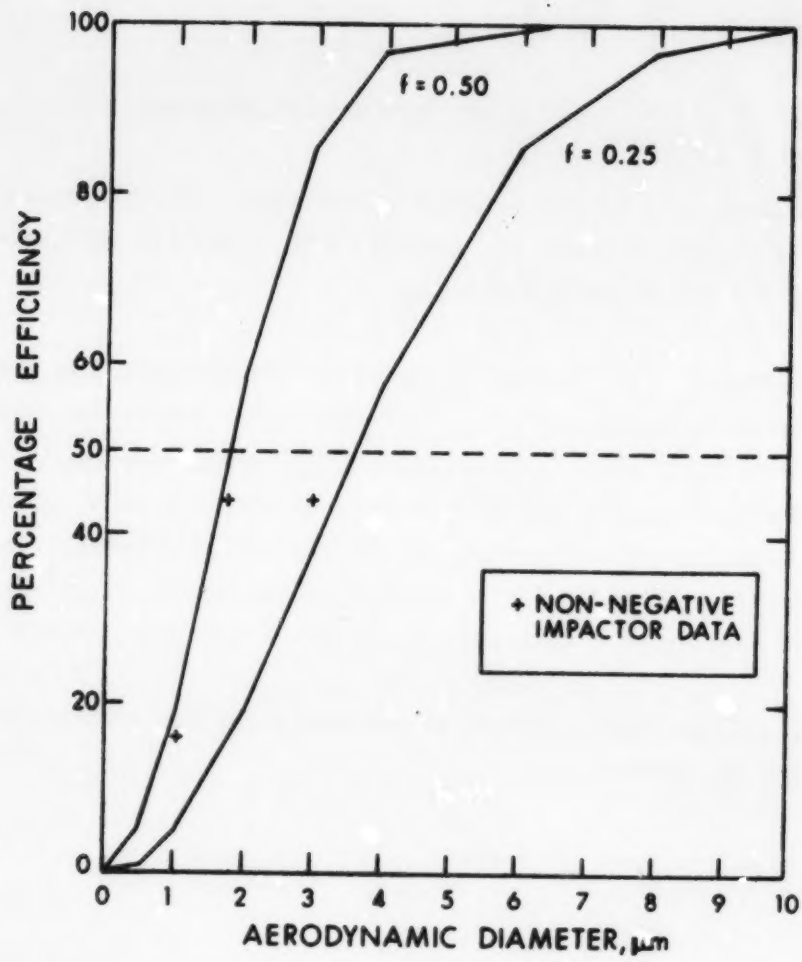

Figure 12. Data and approximate theory predictions (see Table 12) (f = 0.25, 0.50; $Q_L/Q_g = 0.57 \times 10^{-3}$) for Pentapure scrubber

SECTION V

POWER CONSUMPTION AND COSTS

The power used by the scrubber is predominantly the pressure drop of the air going through the scrubber (Δp) times the flow rate of the air (Q_g) in actual volume terms.

The pressure drop across the scrubber was determined by making static pressure measurements at the scrubber inlet (where the samples were obtained) and the scrubber outlet (just before the fan). The inlet readings were made for each total mass sampling point on the traverse, by using the static reading of the pitot-static tube. The outlet readings were made every five minutes during the first half hour the total mass samples were taken, by using an upright unit density oil manometer.

The average values for the measurements for the pressure drops are given in Table 14.

Flow and pressure drop were:

$$Q_g = 25.0 \times 10^3 \text{ ft}^3/\text{min} = 11.8 \text{ m}^3/\text{s}$$

$$\Delta p = 6.06'' \text{ H}_2\text{O} = 1.51 \times 10^3 \text{ N/m}^2$$

Thus, the air power consumption in watts was an average 17.8 kw. A standard estimate of the electrical power necessary to achieve this air flow power is to assume combined efficiency for pumps and fans

of 0.6, which would make the electrical power consumption for this operation 29.7 kw. The fan and motor combination at the site was rated at 75 hp. = 5.6×10^4 w. = 56 kw.

Table 14. AVERAGE PRESSURE DROPS ACROSS PURITY SCRUBBER

Run #	Inlet static pressure ("H_2O)	No. of readings	Outlet static pressure ("H_2O)	No. of readings	Net pressure drop Δp, (" H_2O)	Net pressure drop (N/m^2)
5	1.89	20	7.76	7	5.87	1.46×10^3
6	1.88	15	7.79	7	5.91	1.47×10^3
8	1.86	20	8.17	6	6.31	1.57×10^3
9	1.94	19	7.83	6	5.89	1.47×10^3

WATER CONSUMPTION

The operators of the installation reported that the spray flow was 85 gallons/min. = 5.4×10^{-3} m^3/s. The water flow to air flow ratio was thus about 4.4 gal/1000 s.c.f.m. or 0.46×10^{-3}. Manufacturer's literature puts the water used for the cleaning spray at about 0.7×10^{-4} m^3/m^3 (0.5 gal/1000 ft^3) volume of water to volume of air ratio. Most of the spray was used to cool the gas, approximately 3×10^{-3} m^3/s (50 gal/1000 ft^3) if all the cooling were done by evaporation. There exists some discrepancy between the reported water flow, the calculated cooling water usage, and the manufacturer's literature, but the starting temperature used for the gas (1400°F = 760°F) is only a typical value from the literature, and the water flow was not actually measured for the spray nozzles. For the comparison, we have accepted the manufacturer's value and have accepted his contention that only about 1/3 of this cannot be reused; thus, the water consumption has been placed at 0.17 gal/1000 ft^3 or 0.023×10^{-3} m^3/m^3.

COSTS

The costs of the scrubber are discussed briefly next, with comparison made in terms of a venturi scrubber, which also collects particles through spray scrubbing.

Fixed Costs

The manufacturers have informed us that the equipment and installation costs of the Pentapure scrubber are not substantially different from those for a venturi scrubber. If this were roughly $100,000 for a 19 m^3/s (40,000 c.f.m.) installation (see Scrubber Handbook for cost data and ranges), then the amortization over 20 years would give $5,000 per year cost, the interest on the loan (8 percent of capital investment) would be about $400 yearly, and the insurance about $1,000 per year. These would be as nearly the same for the two types of scrubber as their capital investments are (purchase price plus installation costs).

Variable Costs

Labor and maintenance are estimated as one percent of the capital investment per year, thus about $1,000 per year for both types of scrubber. The cost of electric power (at $0.025 per kw.-hr.) for 19 m^3/s (40,000 c.f.m.) would be:

$$\text{Pentapure power cost} = 60 \text{ kw.} \times 8000 \text{ (hr./yr.)} \times (\$0.025/\text{kw.-hr.})$$
$$= \$12{,}000 \text{ per year.}$$

The mid-range values of the pressure drop for a venturi scrubber having a similar collection efficiency were 3.1×10^2 N/m^2 (1.25" H_2O) and 1.24×10^3 N/m^2 (5" H_2O), depending upon the conditions which

affect the f factor discussed above. This means a power consumption of between about 12 kw. and 50 kw. so that

Venturi power cost = (12 to 50 kw.) (8000 hr./yr.) ($0.025/kw.-hr.)
= $2,400 to $10,000 per year.

The manufacturer reports the cleaning spray (as opposed to the cooling spray) is about 0.7×10^{-4} m^3 per m^3 of air (0.5 gal./1000 $ft.^3$). Cost estimates in the Scrubber Handbook used 1.1×10^{-3} m^3/m^3 (8.4 gal./1000 $ft.^3$) for a venturi scrubber. In both units, much of the water would be reused. If none of the water for the Pentapure scrubber were reused, the cost for a 19 m^3/s (40,000 c.f.m.) unit would be about $6,400 per year, using a water cost of $0.50/100 $ft.^3$. Scrubbers are generally designed so as to reuse the water. If the lower water spray concentration means lower water consumption (that fraction not reused), then the Pentapure might provide a cost savings with respect to water consumption in comparison with the venturi scrubber. Both require some handling of the liquid wastes, the cost of which we do not estimate here.

SECTION VI

APPENDICES

APPENDIX A, IMPACTOR DATA

In Tables VI.1 to VI.12 are the data obtained by the cascade impactor sampling of the Purity Corp. Pentapure Scrubber at the foundry operation on which it was tested. Tests tables give the run number, the data, the location, the impactor flow rate (at impactor conditions) in c.f.m. and m^3/s, the sampling time duration, the total volume samples in that time, the temperature immediately downstream from the impactor, and the concentration as mass per volume dry standard air. Appendix B indicates how these data were handled to make the particle sizing intervals coincide.

Table 15. IMPACTOR DATA, RUN 6, INLET

Run # 6

Date 11/21/74

Location Inlet

Impactor Flow 0.53 CFM, 2.5×10^{-4} m^3/s

Time 11 min = 660 s.

Sample Volume 5.95 ft^3, 1.69×10^{-1} m^3

Impactor Temperature 12 °C

Concentration 0.170 gr/ft^3, 0.387 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	13.0	0.0015	2.3	0.009	2.3
2	8.1	0.0009	1.4	0.005	3.7
3	5.5	0.0015	2.3	0.009	6.0
4	3.8	0.0011	1.7	0.007	7.7
5	2.4	0.0020	3.1	0.012	10.8
6	1.23	0.0182	27.8	0.108	38.6
7	0.75	0.0135	20.6	0.080	59.2
8	0.51	0.0104	15.9	0.062	75.1
Back up filter		0.0163	24.9	0.096	
Total		0.0654		0.387	

Table 16. IMPACTOR DATA, RUN 7, INLET

Run # 7

Date 11/22/74

Location Inlet

Impactor Flow 0.50 CFM, 2.4×10^{-4} m^3/s

Time 4 min = 240 s.

Sample Volume 2.05 ft^3, 5.81×10^{-2} m^3

Impactor Temperature 12 °C

Concentration 0.298 gr/ft^3, 0.680 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	13.4	0.0010	2.5	0.017	2.5
2	8.4	0.0020	5.1	0.034	7.6
3	5.6	0.0018	4.6	0.031	12.2
4	3.9	0.0011	2.8	0.019	15.0
5	2.4	0.0009	2.3	0.015	17.3
6	1.27	0.0021	5.3	0.036	22.6
7	0.77	0.0039	9.9	0.067	32.5
8	0.53	0.0077	19.5	0.133	52.0
Back up filter		0.0190	48.0	0.327	
Total		0.0395		0.680	

Table 17. IMPACTOR DATA, RUN 8A, INLET

Run # 8A

Date 11/25/74

Location Inlet

Impactor Flow 0.72 CFM, 3.4×10^{-4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.64 ft^3, 7.48×10^{-2} m^3

Impactor Temperature 132°C

Concentration 0.203 gr/ft^3, 0.464 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.7	0.0004	1.1	0.005	1.1
2	8.0	0.0008	2.4	0.011	3.5
3	5.3	0.0006	1.7	0.008	5.2
4	3.7	0.0009	2.6	0.012	7.8
5	2.3	0.0006	1.7	0.008	9.5
6	1.20	0.0013	3.7	0.017	13.2
7	0.73	0.0023	6.7	0.031	19.9
8	0.49	0.0057	16.4	0.076	36.3
Back up filter		0.0221	63.7	0.295	
Total		0.0347		0.464	

Table 18. IMPACTOR, DATA, RUN 8B, INLET

Run # 8B

Date 11/25/74

Location Inlet

Impactor Flow 0.77 CFM, 3.6×10^{-4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.78 ft^3, 7.87×10^{-2} m^3

Impactor Temperature 139°C

Concentration 0.205 gr/ft^3, 0.470 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.4	0.0000	≤ 0.9	≤0.004	
2	7.7	0.0003	≤ 0.9	≤0.004	
3	5.2	-0.0002	≤ 0.9	≤0.004	0.9
4	3.6	0.0005	1.3	0.006	2.2
5	2.25	0.0005	1.3	0.006	3.5
6	1.16	0.0015	4.0	0.019	7.5
7	0.70	0.0063	17.0	0.080	24.5
8	0.47	0.0110	29.8	0.140	54.3
Back up filter		0.0169	45.7	0.215	
Total		0.0370		0.470	

Table 19. IMPACTOR DATA, RUN 9A, INLET

Run # 9A

Date 11/26/74

Location Inlet

Impactor Flow 0.73 CFM, 3.4×10^{4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.66 ft^3, 7.53×10^{2} m^3

Impactor Temperature 123°C

Concentration 0.170 gr/ft^3, 0.388 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.6	0.0000	≤ 1.0	≤0.004	
2	7.8	0.0001	≤ 1.0	≤0.004	
3	5.2	0.0000	≤ 1.0	≤0.004	
4	3.6	0.0003	≤ 1.0	≤0.004	
5	2.3	0.0002	≤ 1.0	≤0.004	2.2
6	1.18	0.0010	3.4	0.013	5.6
7	0.71	0.0013	4.4	0.017	10.0
8	0.48	0.0056	19.1	0.074	29.1
Back up filter		0.0207	70.9	0.275	
Total		0.0292		0.388	

Table 20. IMPACTOR DATA, RUN 9B, INLET

Run # 9B

Date 11/26/74

Location Inlet

Impactor Flow 0.69 CFM, 3.3×10^{-4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.74 ft^3, 7.76×10^{-2} m^3

Impactor Temperature 88°C

Concentration 0.131 gr/ft^3, 0.300 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.5	0.0000	≤ 1.3	≤0.004	
2	7.8	0.0002	≤ 1.3	≤0.004	
3	5.2	0.0001	≤ 1.3	≤0.004	
4	3.6	0.0001	≤ 1.3	≤0.004	
5	2.3	0.0003	≤ 1.3	≤0.004	3.1
6	1.17	0.0015	6.3	0.019	9.4
7	0.71	0.0045	19.3	0.058	28.7
8	0.48	0.0075	32.3	0.097	61.0
Back up filter		0.0091	39.0	0.117	
Total		0.0233		0.300	

Table 21. IMPACTOR DATA, RUN 6, OUTLET

Run # 6

Date 11/21/74

Location Outlet

Impactor Flow 0.58 CFM, 2.7×10^{-4} m^3/s

Time 6 min = 360 s.

Sample Volume $3.17 ft^3$, 8.98×10^{-2} m^3

Impactor Temperature 49 °C

Concentration 0.213 gr/ft^3, 0.487 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	13.0	-0.0012	≤ 0.6	≤0.003	
2	8.2	0.0003	≤ 0.6	≤0.003	0.7
3	5.5	0.0010	2.3	0.011	3.0
4	3.8	0.0010	2.3	0.011	5.3
5	2.4	0.0005	1.2	0.006	6.5
6	1.23	0.0020	4.5	0.022	11.0
7	0.75	0.0063	14.4	0.070	25.4
8	0.51	0.0113	25.9	0.126	51.3
Back up filter		0.0213	48.7	0.237	
Total		0.0437		0.487	

Table 22. IMPACTOR DATA, RUN 7, OUTLET

Run # 7

Date 11/22/74

Location Outlet

Impactor Flow 0.88 CFM, 4.2×10^{-4} m^3/s

Time 6 min = 360 s.

Sample Volume 3.08 ft^3, 8.72×10^{-2} m^3

Impactor Temperature 233 °C

Concentration 0.249 gr/ft^3, 0.571 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.5	0.0006	1.2	0.007	1.2
2	7.8	0.0004	0.8	0.005	2.0
3	5.2	0.0004	0.8	0.005	2.8
4	3.6	0.0006	1.2	0.007	4.0
5	2.3	0.0010	2.0	0.011	6.0
6	1.17	0.0010	2.0	0.011	8.0
7	0.70	0.0049	9.8	0.056	17.8
8	0.47	0.0190	38.2	0.218	56.0
Back up filter		0.0219	44.0	0.251	
Total		0.0498		0.571	

Table 23. IMPACTOR DATA, RUN 8A, OUTLET

Run # 8A

Date 11/25/74

Location Outlet

Impactor Flow 0.70 CFM, 3.3×10^{-4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.71 ft^3, 7.67×10^{-2} m^3

Impactor Temperature 58 ^oC

Concentration 0.172 gr/ft^3, 0.392 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.0	0.0000	≤ 1.0	≤0.004	
2	7.5	0.0000	≤ 1.0	≤0.004	
3	5.0	0.0000	≤ 1.0	≤0.004	
4	3.5	0.0001	≤ 1.0	≤0.004	
5	2.2	0.0001	≤ 1.0	≤0.004	0.8
6	1.13	0.0006	2.0	0.008	2.8
7	0.68	0.0018	5.9	0.023	8.7
8	0.46	0.0070	23.2	0.091	31.9
Back up filter		0.0205	68.1	0.267	
Total		0.0301		0.392	

Table 24. IMPACTOR DATA, RUN 8B, OUTLET

Run # 8B

Date 11/25/74

Location Outlet

Impactor Flow 0.66 CFM, 3.1×10^{-4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.79 ft^3, 7.90×10^{-2} m^3

Impactor Temperature 76°C

Concentration 0.191 gr/ft^3, 0.437 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.6	-0.0001	≤ 0.9	≤0.004	
2	7.9	0.0000	≤ 0.9	≤0.004	
3	5.3	0.0000	≤ 0.9	≤0.004	
4	3.7	-0.0001	≤ 0.9	≤0.004	
5	2.3	0.0003	≤ 0.9	≤0.004	0.9
6	1.19	0.0009	2.5	0.011	3.4
7	0.72	0.0041	11.9	0.052	15.3
8	0.49	0.0100	29.1	0.127	44.4
Back up filter		0.0192	55.6	0.243	
Total		0.0345		0.437	

Table 25. IMPACTOR DATA, RUN 9A, OUTLET

Run # 9A

Date 11/26/74

Location Outlet

Impactor Flow 0.59 CFM, 2.8×10^{-4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.70 ft^3, 7.65×10^{-2} m^3

Impactor Temperature 44 ^oC

Concentration 0.153 gr/ft^3, 0.349 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	12.9	-0.0003	≤ 1.1	≤0.004	
2	8.0	-0.0001	≤ 1.1	≤0.004	
3	5.4	0.0000	≤ 1.1	≤0.004	
4	3.7	-0.0002	≤ 1.1	≤0.004	
5	2.3	0.0000	≤ 1.1	≤0.004	
6	1.21	0.0005	2.0	0.007	1.7
7	0.74	0.0015	5.7	0.020	7.4
8	0.50	0.0042	15.8	0.055	23.2
Back up filter		0.0205	76.8	0.268	
Total		0.0267		0.349	

Table 26. IMPACTOR DATA, RUN 9B, OUTLET

Run # 9B

Date 11/26/74

Location Outlet

Impactor Flow 0.46 CFM, 2.2×10^{-4} m^3/s

Time 5 min = 300 s.

Sample Volume 2.20 ft^3, 6.23×10^{-2} m^3

Impactor Temperature 29 °C

Concentration 0.185 gr/ft^3, 0.424 g/m^3

Stage	Aerodynamic diameter (μm)	Net weight (g)	% on stage	Concentration (g/m^3)	% ≥ stated size
1	14.3	0.0000	≤ 1.2	≤0.005	
2	8.9	0.0000	≤ 1.2	≤0.005	
3	6.0	-0.0002	≤ 1.2	≤0.005	
4	4.2	-0.0008	≤ 1.2	≤0.005	
5	2.6	0.0002	≤ 1.2	≤0.005	0.6
6	1.35	0.0010	3.8	0.016	4.4
7	0.83	0.0036	13.7	0.058	18.1
8	0.57	0.0064	24.3	0.103	42.4
Back up filter		0.0152	57.6	0.244	
Total		0.0264		0.424	

APPENDIX B, COMPARING SIZE DISTRIBUTION DATA HAVING DIFFERENT SIZING INTERVALS

For a variety of reasons, particle size distribution data may have been obtained by multi-stage or multi-channel instruments with different size intervals. To change concentration reading M_i, obtained for particles between a_{i-1} and a_i, into concentration readings M_i^* over the interval a_{i-1}^* to a_i^* one estimates the concentration in the portion of the interval which is different by using the average concentration per unit particle size obtained from the intervals adjacent to the portion in question. This is shown in Figure VI-1, and the equations are given for making this transformation. This is, essentially, a linear interpolation.

To apportion the material M_i collected between a_{i-1} and a_i to standard intervals a_{i-1}^* to a_i^*:

$$M_1^* = M_1 + \frac{1}{2}(a_1^* - a_1)\left[M_1/(a_1 - a_0) + M_2/(a_2 - a_1)\right]$$

$$M_2^* = M_2 + \frac{1}{2}(a_2^* - a_2)\left[M_2/(a_2 - a_1) + M_3/(a_3 - a_2)\right]$$

$$- \frac{1}{2}(a_1^* - a_1)\left[M_1/(a_1 - a_0) + M_2/(a_2 - a_1)\right]$$

$$M_3^* = M_3 + \frac{1}{2}(a_3^* - a_3)\left[M_4/(a_4 - a_3) + M_3/(a_3 - a_2)\right]$$

$$- \frac{1}{2}(a_2^* - a_2)\left[M_2/(a_2 - a_1) + M_3/(a_3 - a_2)\right]$$

By induction,

$$M_i^* = M_i + \Delta M_i - \Delta M_{i-1}$$

$$\Delta M_i = (a_i^* - a_i)\left[M_i/(a_i - a_{i-1}) + M_{i+1}/(a_{i+1} - a_i)\right]$$

$$\Delta M_0 = 0.$$

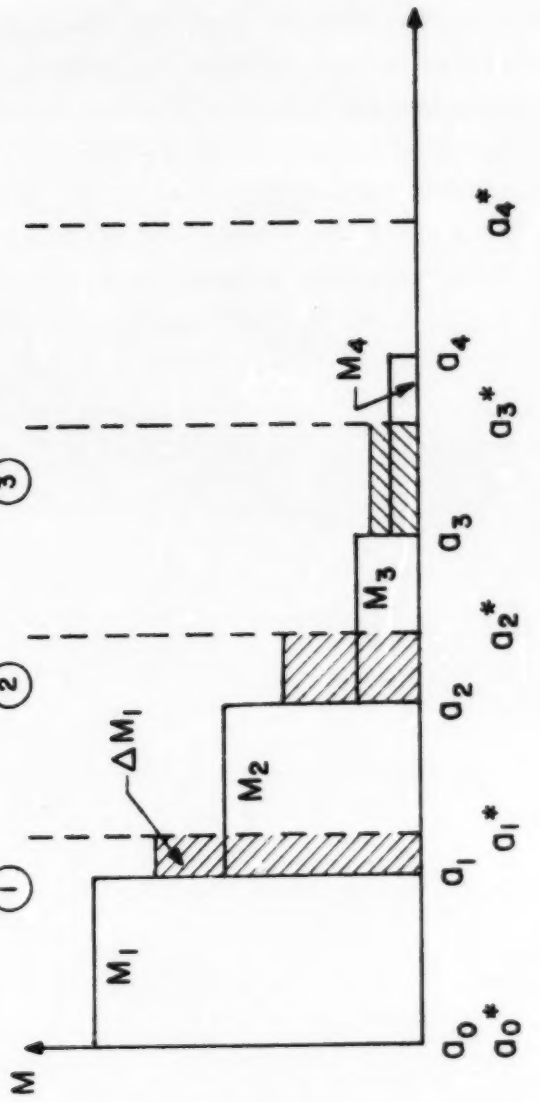

Figure 13. Interval adjustment diagram

SECTION VII

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